Transient Optimization for the Betterment of Turbine Electrified Energy Management

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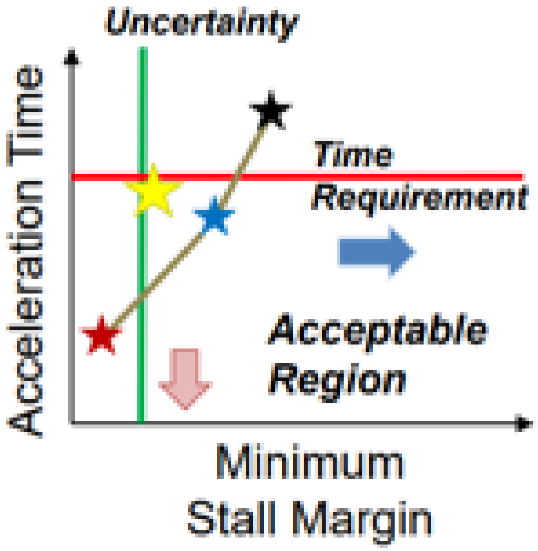
Background

- Challenge – maintaining operability during engine power transients throughout a vast operating envelope
- Engine design and associated performance is constrained by operability requirements
  - Improving operability can enable better efficiency and/or reduced weight
- A related study demonstrated operability improvements by optimizing fuel flow transient limit logic
- Turbine Electrified Energy Management (TEEM) by leveraging an electrical power system



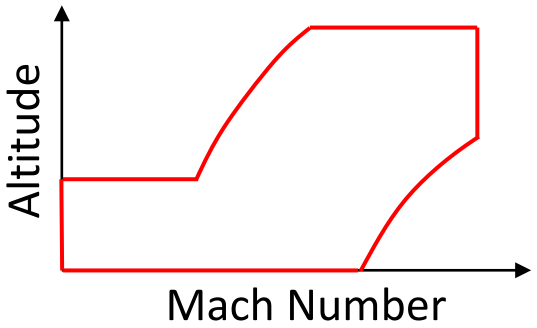
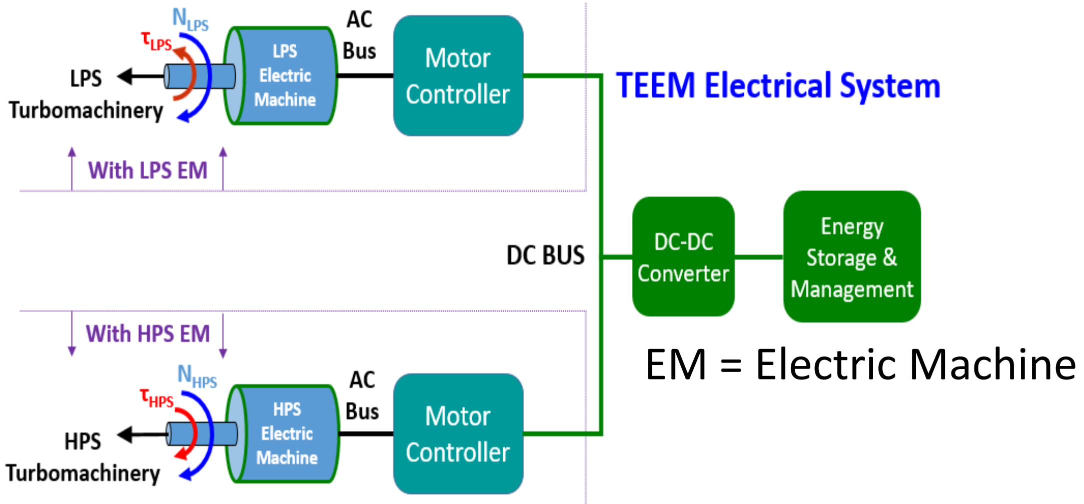
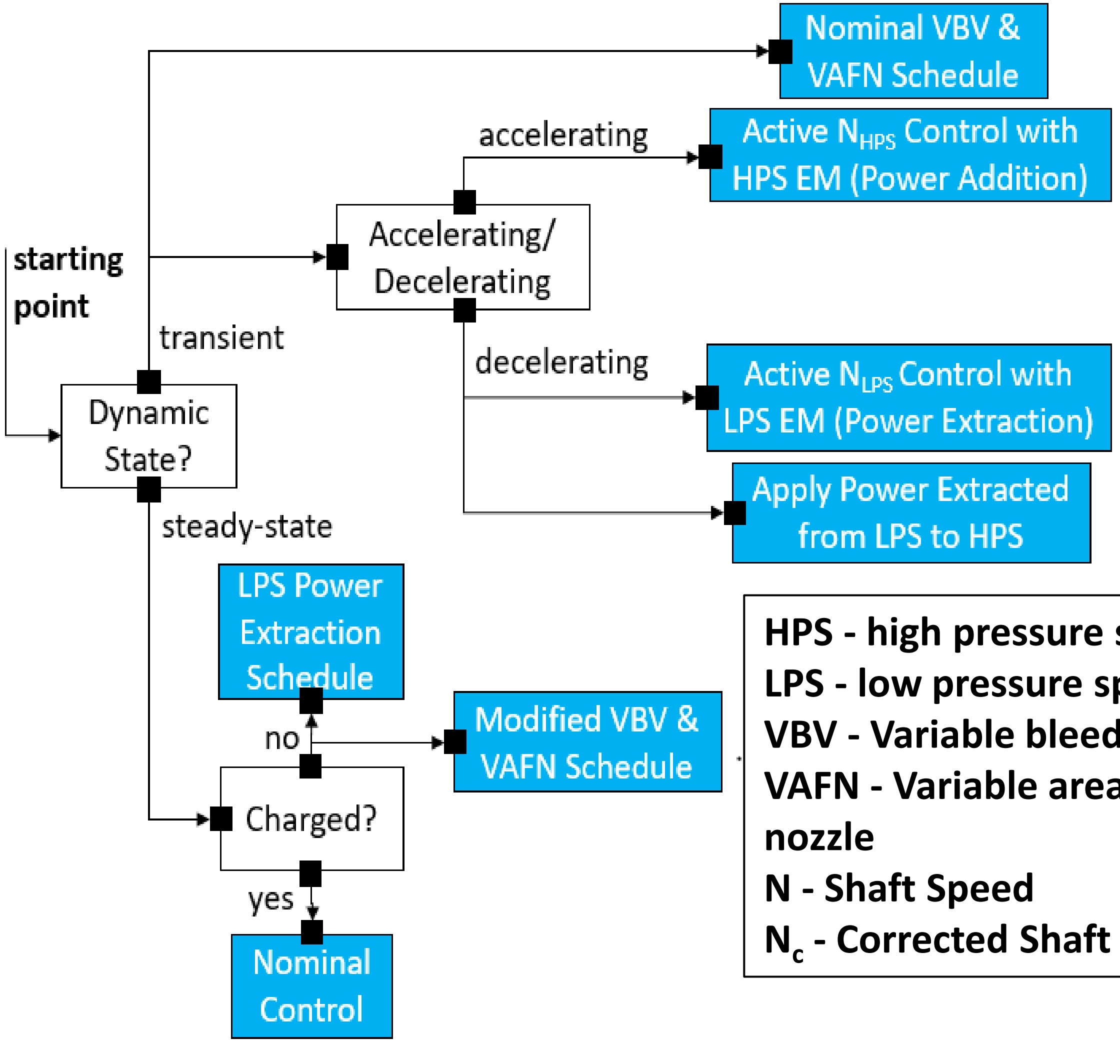


*Image Credit to NASA and the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)



Background (cont.)

- Various applications of TEEM have been illustrated in literature
- The tendency is to:
  - Add power to the HPS during accelerations
  - Transfer power from the LPS to the HPS during decelerations
    - Alternatives: Extract power from the LPS or inject power to the HPS
  - Prior applications use proportional integral (PI) controllers that seek to control shaft speeds to keep them coordinated with the engine actuation (fuel flow rate)
- Activation/deactivation logic is present to determine when the engine is experiencing a transient

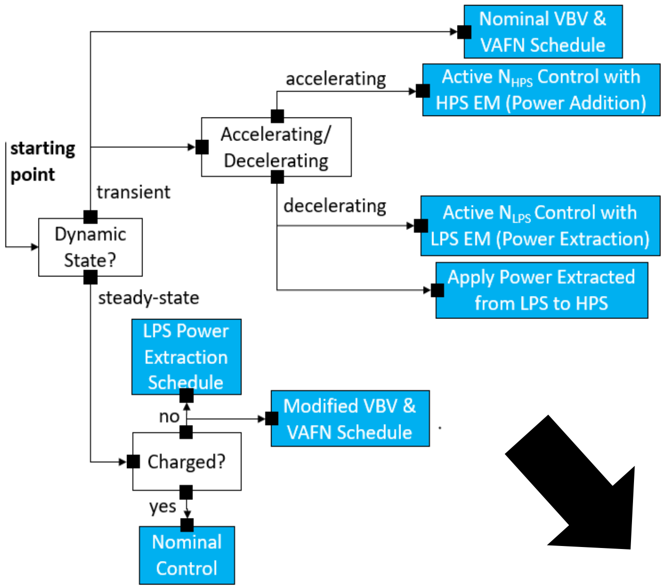


HPS - high pressure spool
LPS - low pressure spool
VBV - Variable bleed valve
VAFN - Variable area fan nozzle
N - Shaft Speed
N_c - Corrected Shaft Speed

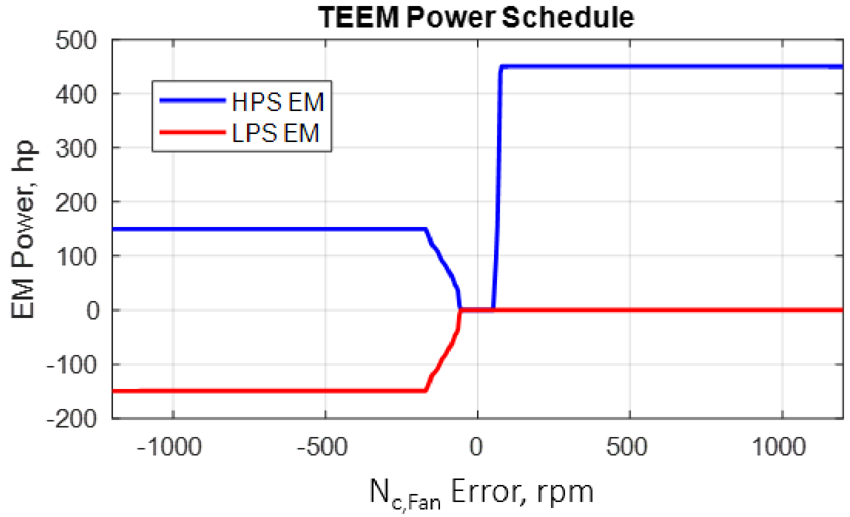
Background (cont.)

- Hypotheses:
  - Optimized fuel flow transient limit logic will reduce power system requirements for TEEM
  - Optimization techniques can be employed to further improve the effectiveness of TEEM
  - An open loop schedule-based TEEM control approach can be derived from optimization results and used in place of a close loop controller.

Prior Closed-Loop Logic with Activation

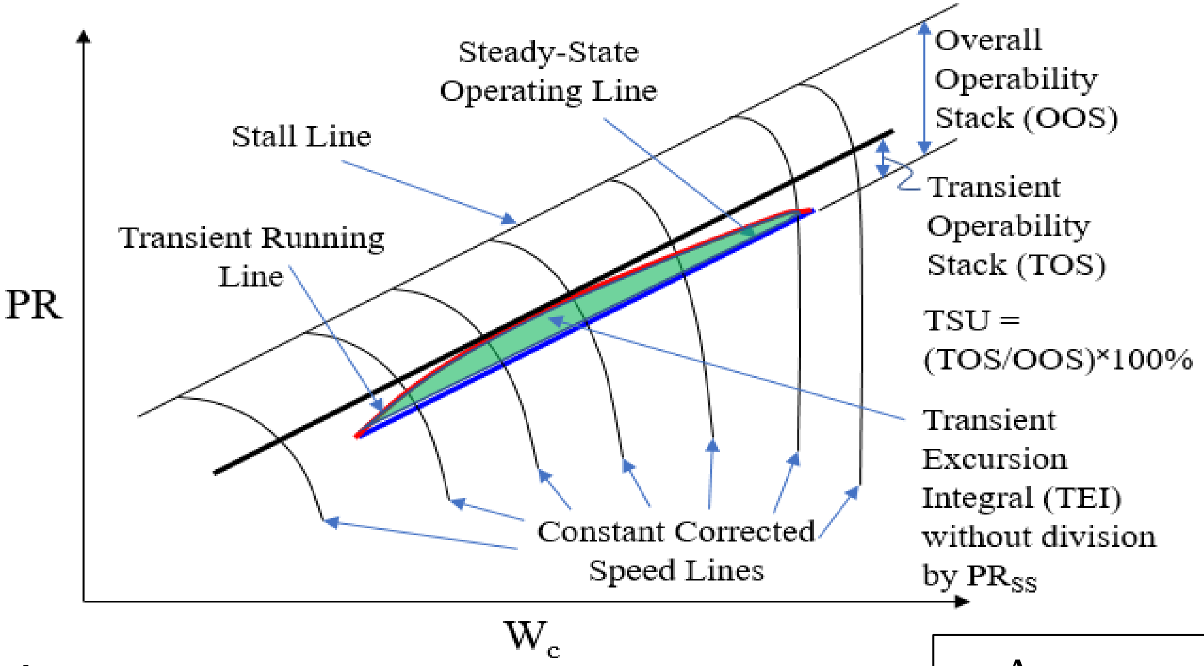


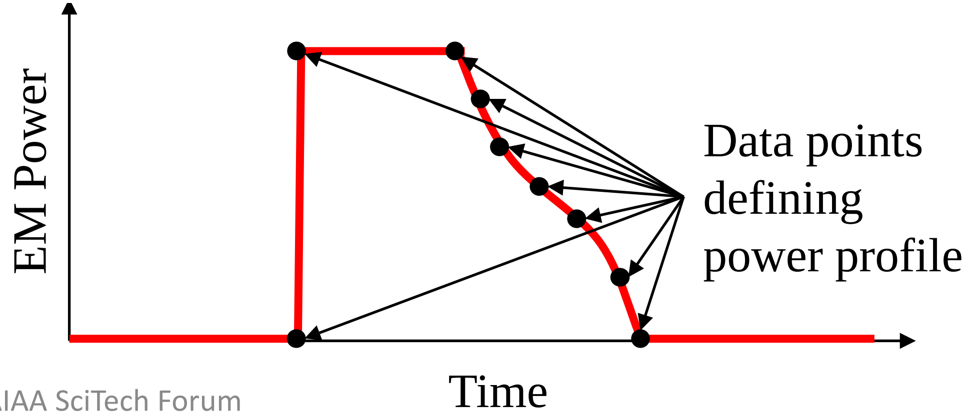
Simplified Scheduled Approach



Overview of Optimization Approach

- A genetic algorithm is applied to identify the "optimal" EM power input profiles that maximizes operability as defined by the transient excursion integral (TEI)
- The fuel flow, w_f, profile is prescribed (leveraged from prior study)
- The inputs are the EM power inputs at various times during the transient, under some constraints
  - Acceleration only uses power input on the HPS
  - Deceleration uses either power transfer from the LPS to the HPS, power extraction from the LPS, or power injection to the HPS
  - Power level starts out high & remains there for some duration
  - The power level decreases monotonically to zero
- The fitness of each solution is judged based on the TEI
- An iterative root solving technique is leveraged to stretch/compress the fuel flow input profile to achieve the desired thrust response time
- Optimized results are used to derive a power schedule for implementing TEEM





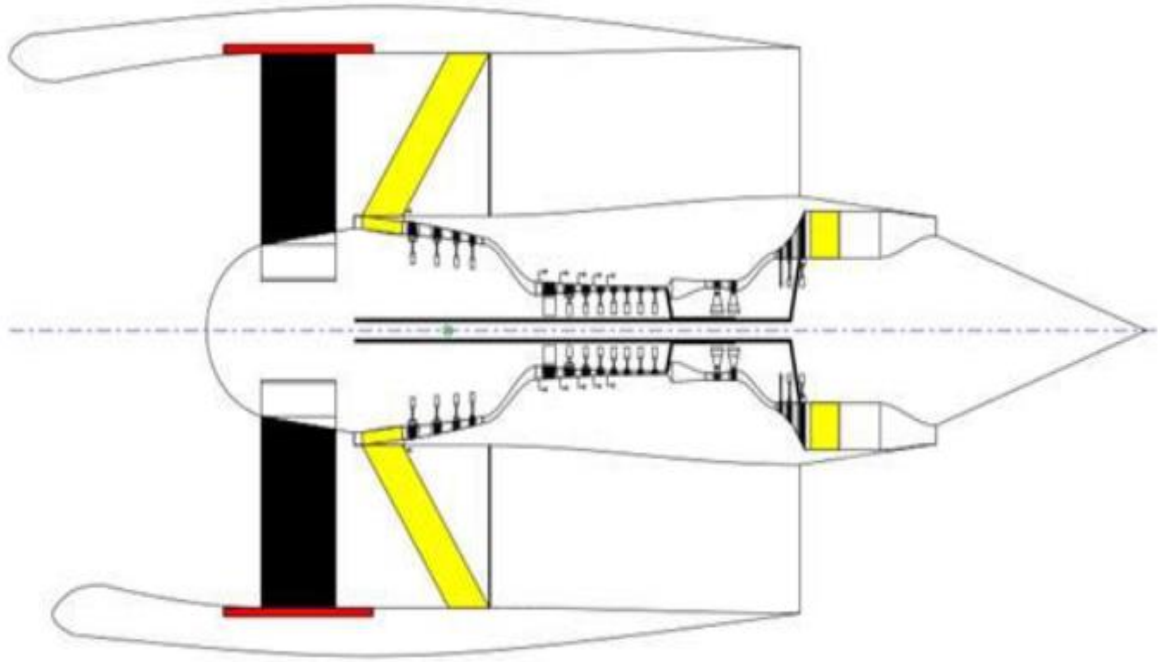
Acronyms

TSU = transient stack usage
PR = pressure ratio
W_c = corrected flow rate

Application - AGTF30 Engine

- Conceptual two-spool geared turbofan
- Produces ~30,000 lb_f of force at sea level static (SLS) conditions
- Envisioned for single-aisle applications
- Included advanced technologies
  - Compact core
  - Variable area fan nozzle
- MATLAB/Simulink® model developed with the Toolbox for Modeling & Analysis of Thermodynamic Systems (T-MATS)
- Includes a baseline controller with representative performance
- Includes engine health parameters

Advanced Geared Turbofan 30,000 lb_f (AGTF30)



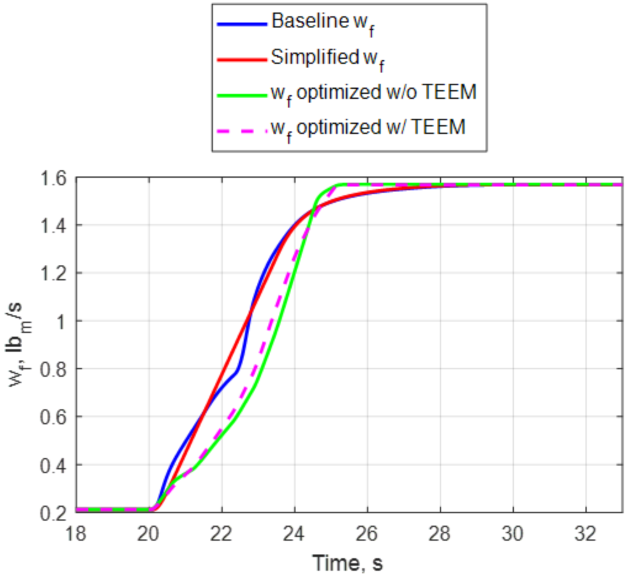
Optimization Results – A Quick Comparison

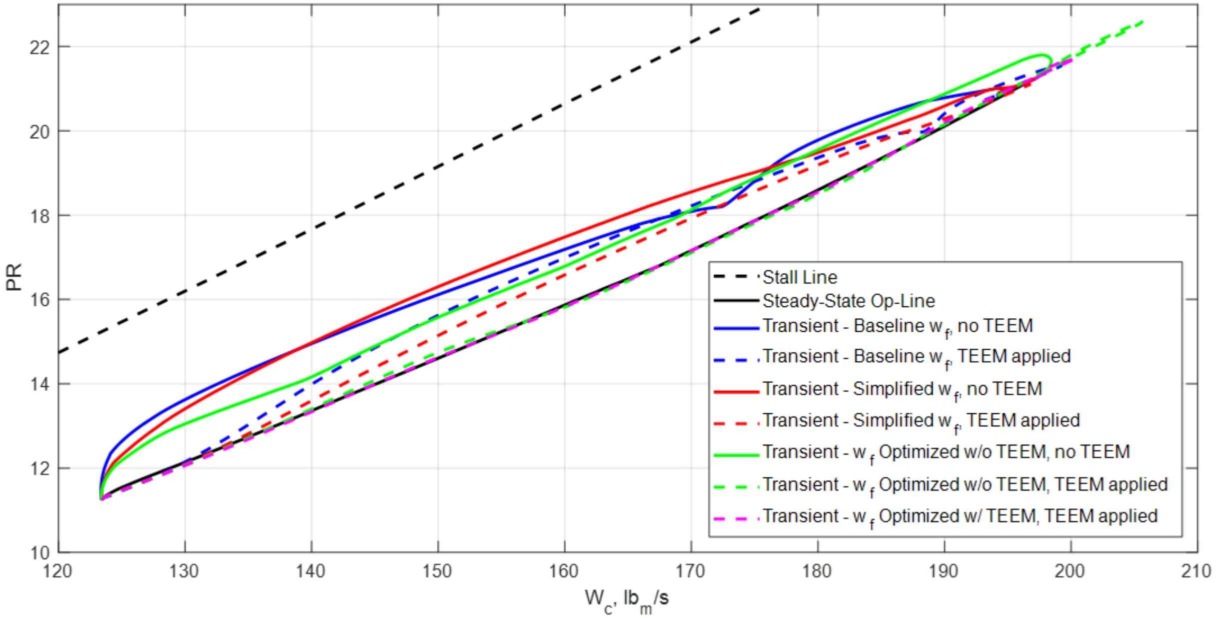
Simulation Characteristics

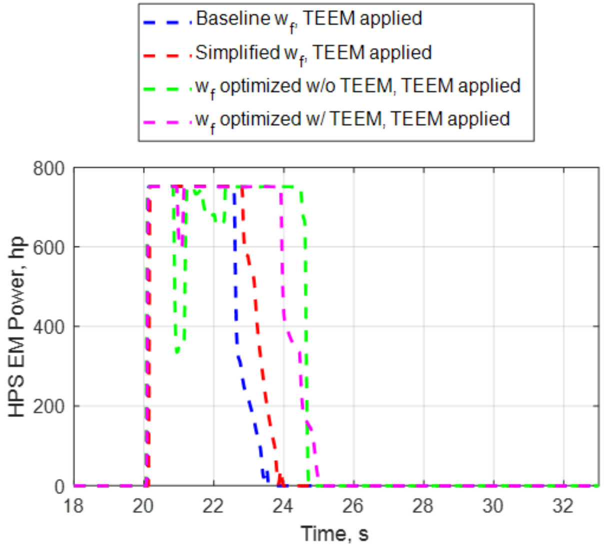
- Sea Level Static
- Acceleration
- Baseline TEEM controller applied when TEEM is used

Conclusions

- Significant benefit with TEEM
- Significantly enhanced benefit with the optimized w_f profile
- Optimizing the w_f profile with and without TEEM has only a small impact



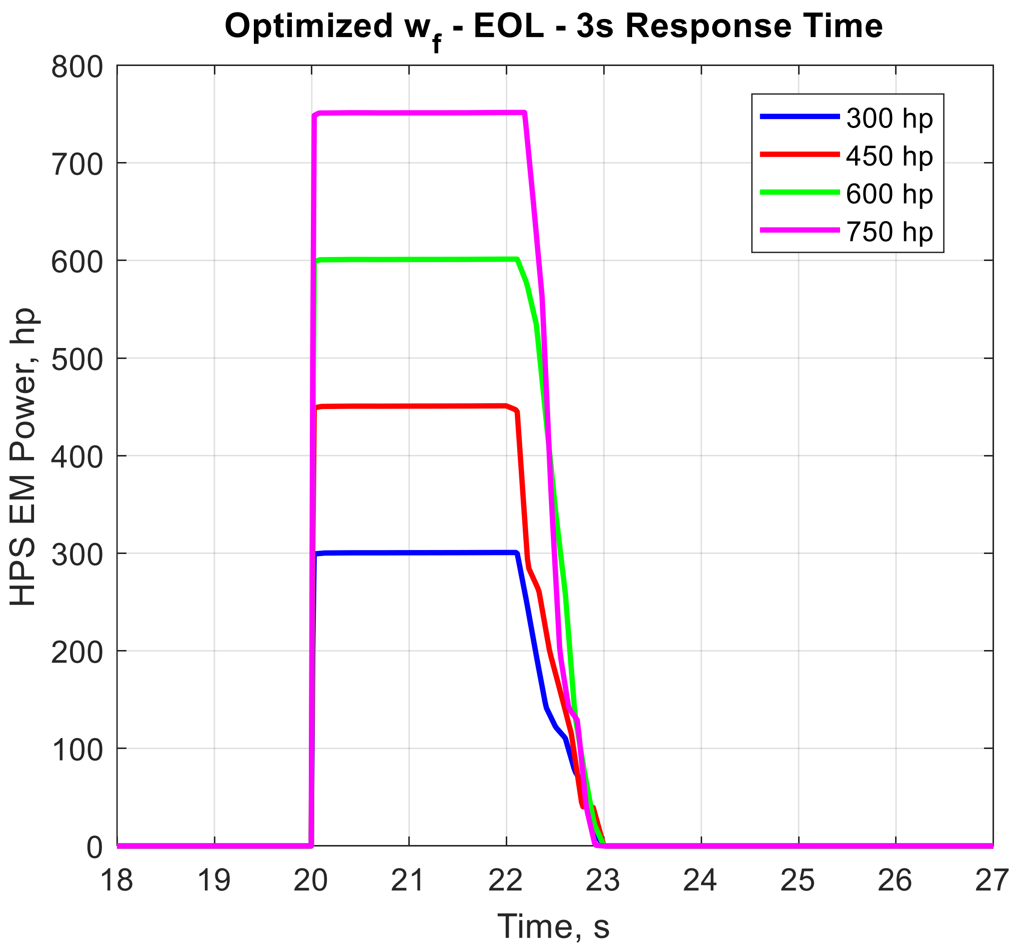




Option	TSU, %	TEI, lb_m/s	Energy Usage, kW-hr
Baseline w_f, no TEEM	37.7	5.85	0
Baseline w_f, TEEM applied	23.5	3.14	0.42
Simplified w_f, no TEEM	37.9	5.98	0
Simplified w_f, TEEM applied	16.0	1.89	0.49
w_f optimized without TEEM, no TEEM	22.4	4.20	0
w_f optimized without TEEM, TEEM applied	3.1	0.28	0.67
w_f optimized with TEEM, TEEM applied	2.5	0.17	0.65

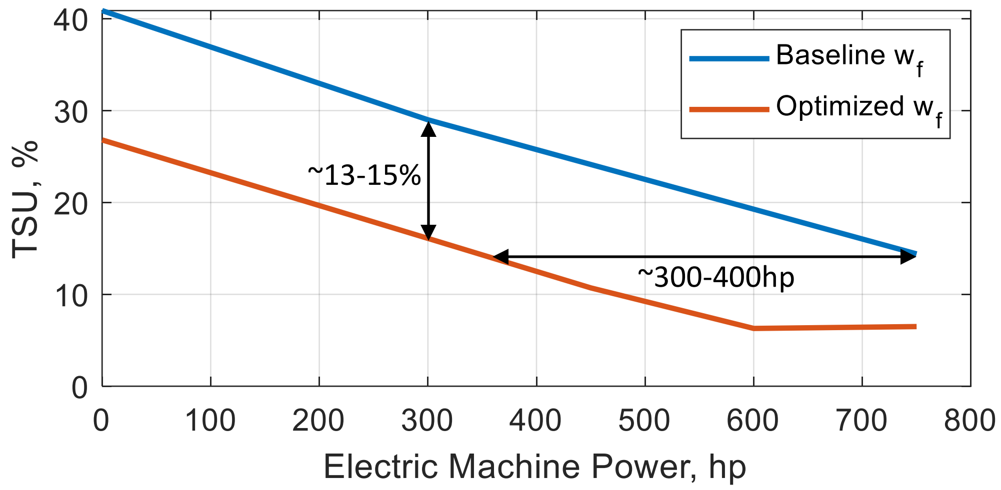
Optimization Results – Trade Space Analysis - Acceleration

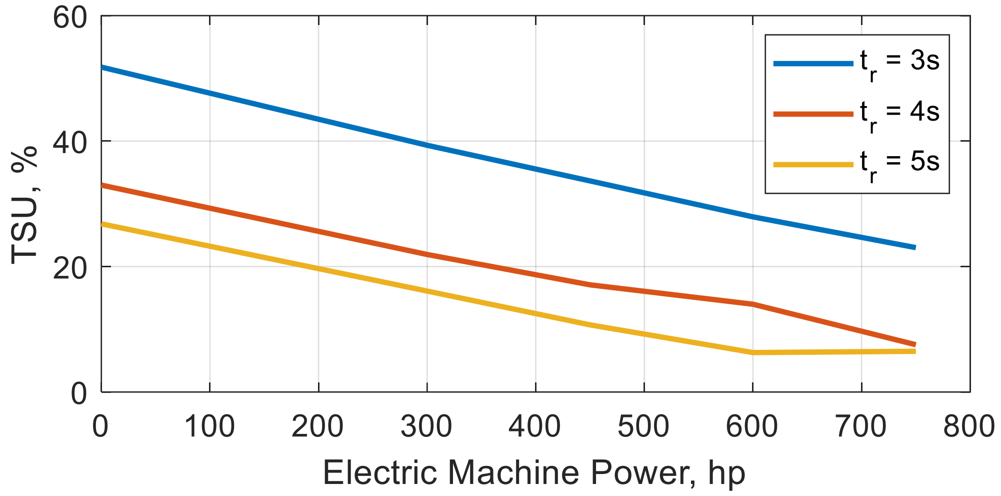
- Goal: Quantify the operability impact for various options to identify the trades between operability, thrust responsiveness, and power system requirements
- Conducted optimizations for a variety of conditions
  - Accelerations & decelerations
  - New and End of Life (EOL) engine
  - Baseline & Optimized w_f profile
  - Various EM power levels
  - Various thrust response times
  - Various EM usage scenarios for decelerations (power transfer vs. HPS injection vs. LPS extraction)
- Example of optimized profiles shown to the right →

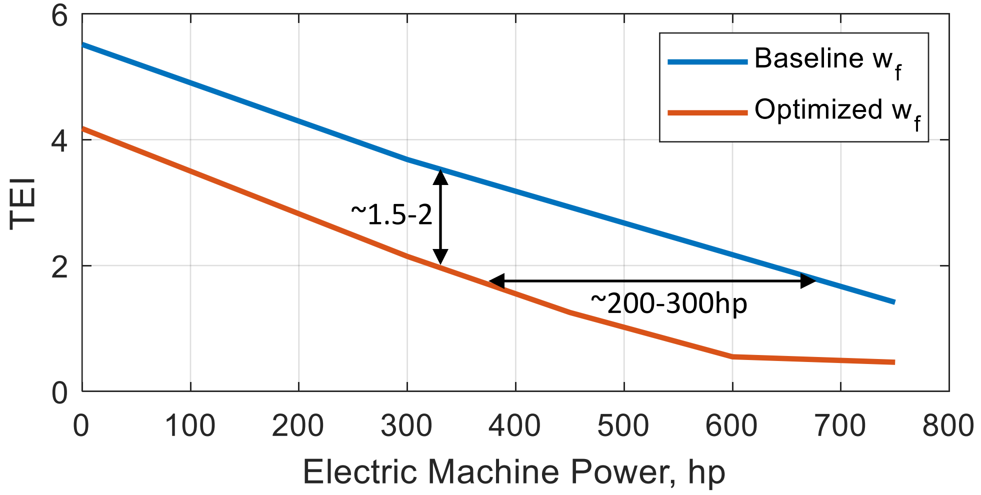


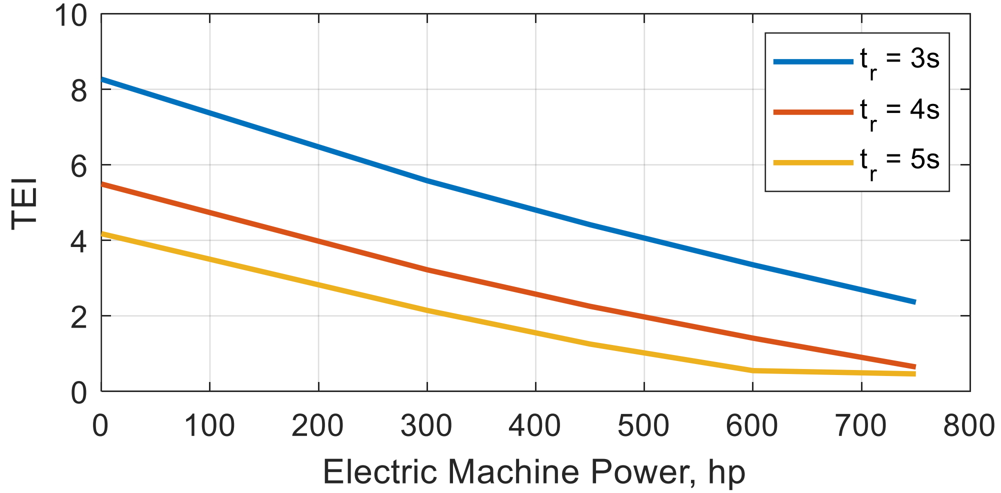
Optimization Results – Trade Space Analysis - Acceleration

5s Thrust Response Time



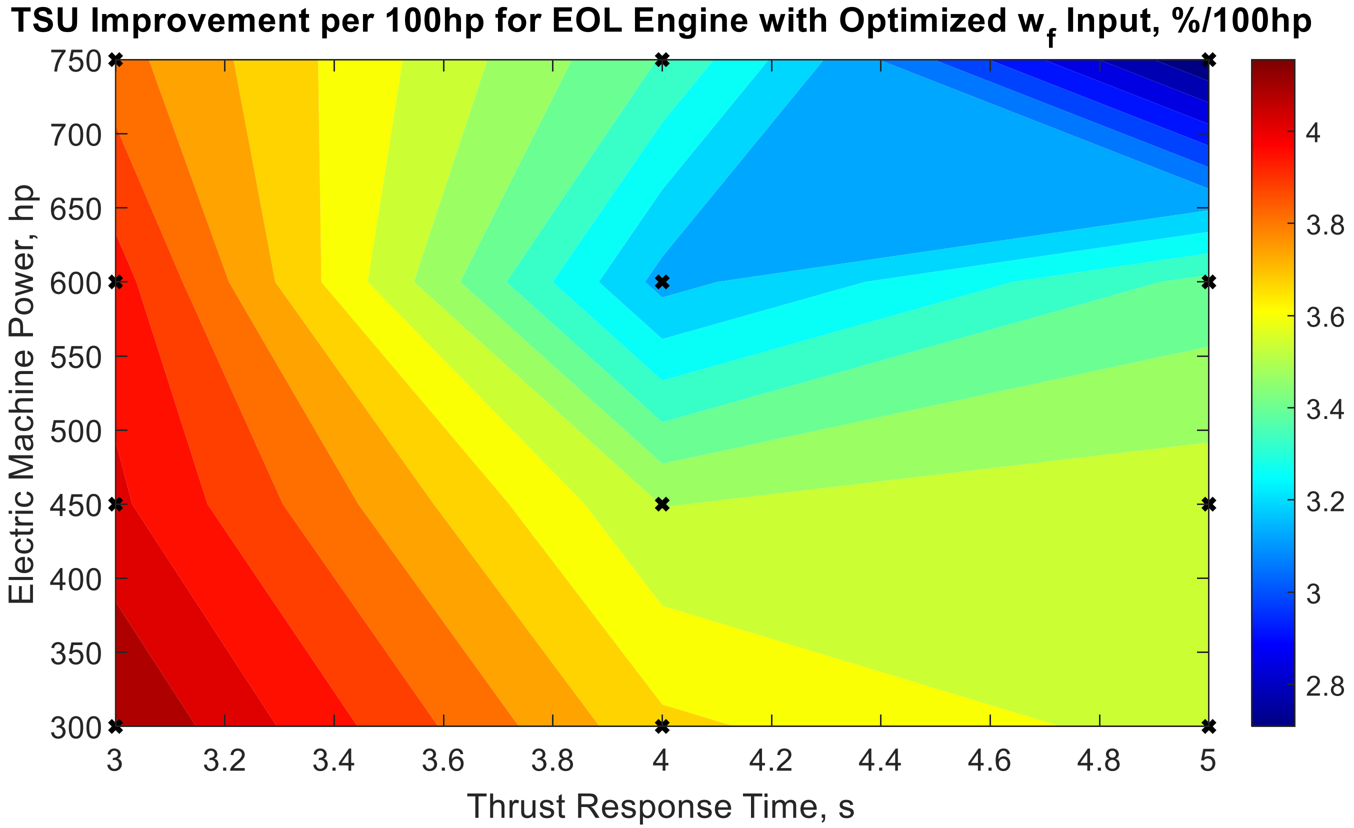






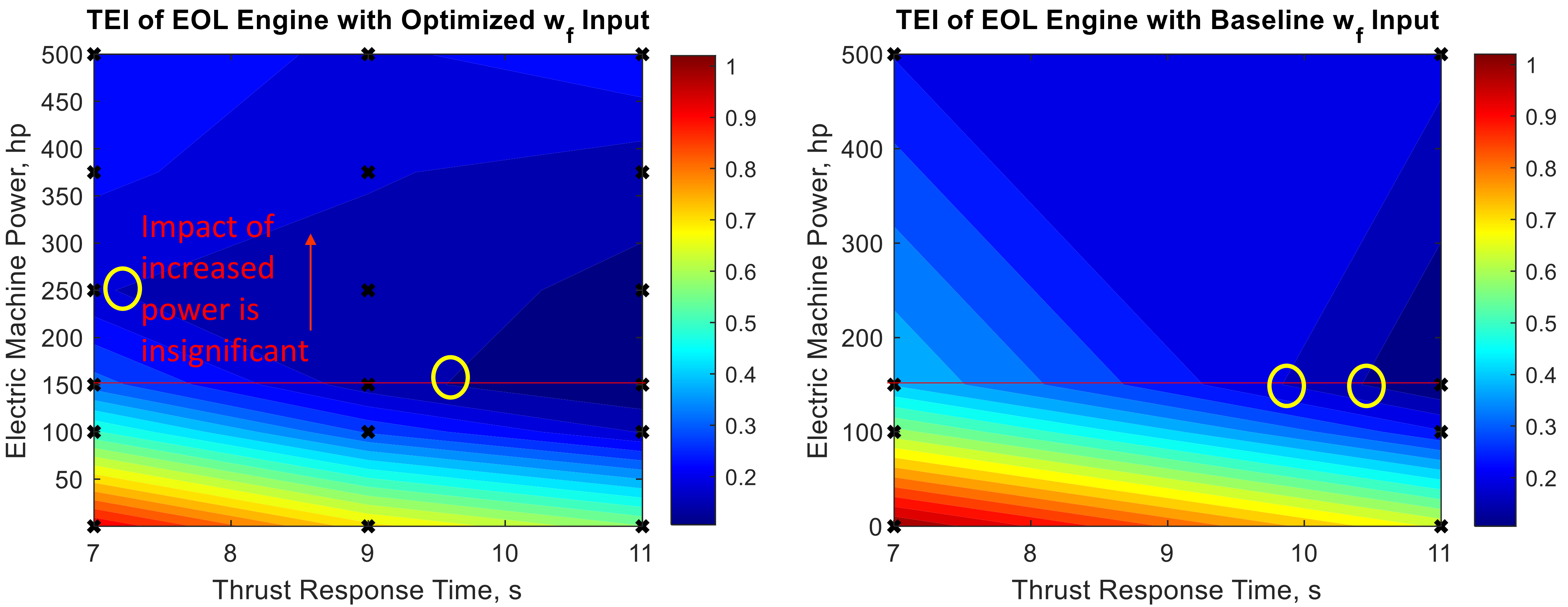
EOL Engine **t_r – Thrust Response Time**

Optimization Results – Trade Space Analysis - Acceleration



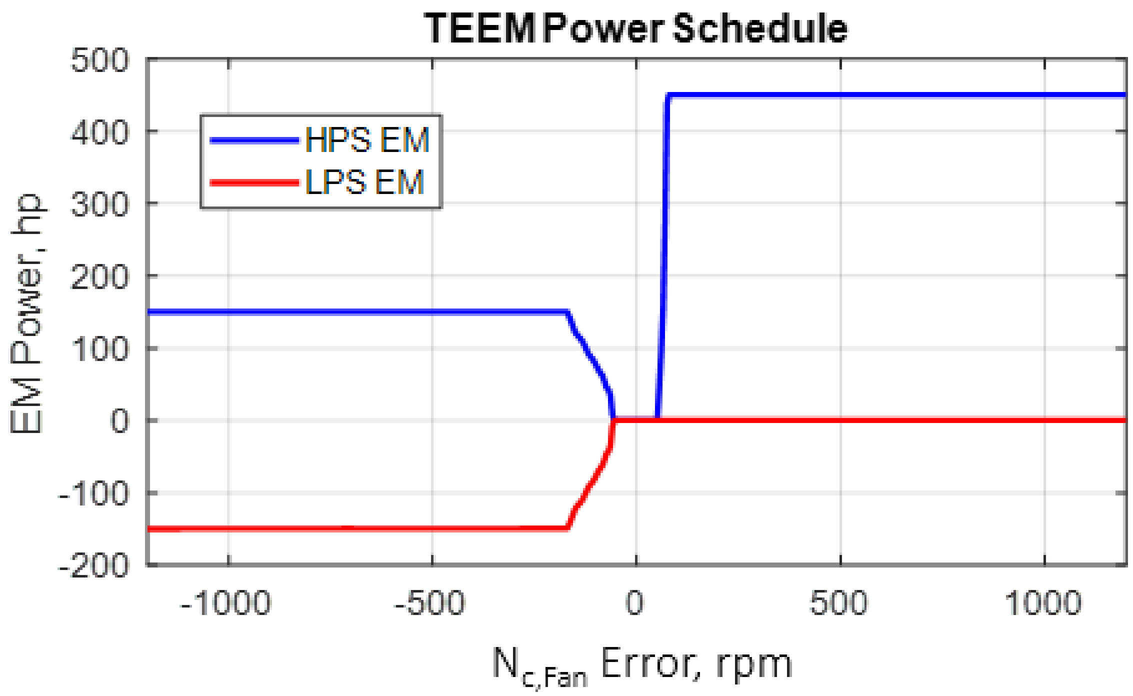
- Impact tends to increase with decreasing thrust response time
- Effectiveness tends to dwindle as EM power increases

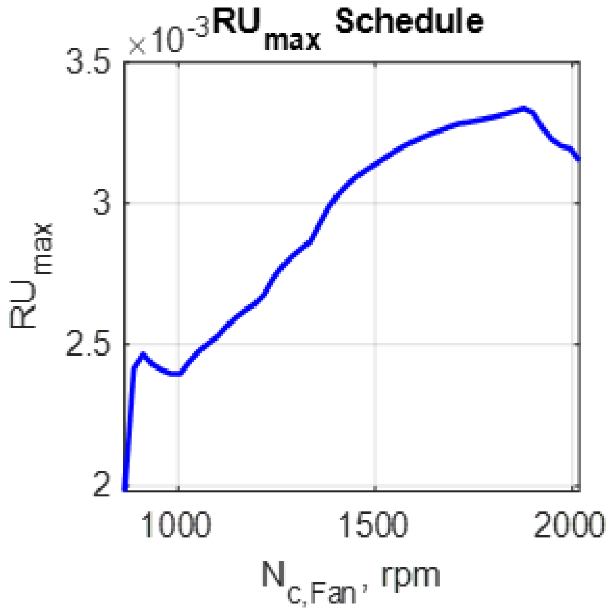
Optimization Results – Trade Space Analysis - Deceleration

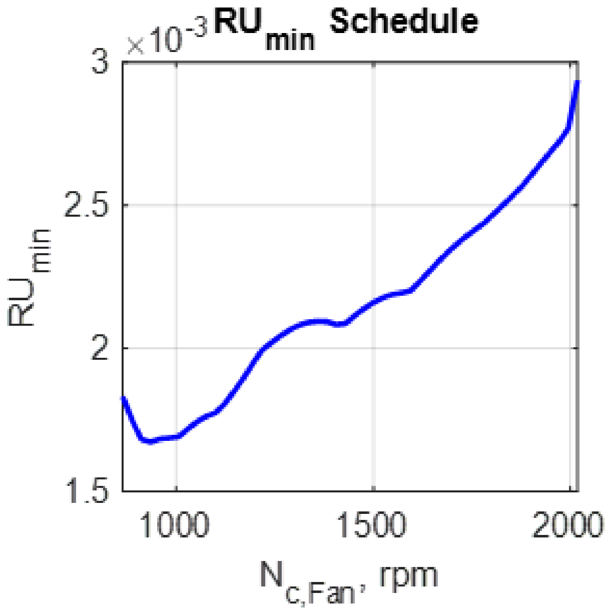


- There is no need to increase the power transfer above 150hp
- A minimum TEI is achieved for a given thrust response time and shifts to higher power transfer values as the thrust response time decreases

Schedule-Based Control Results

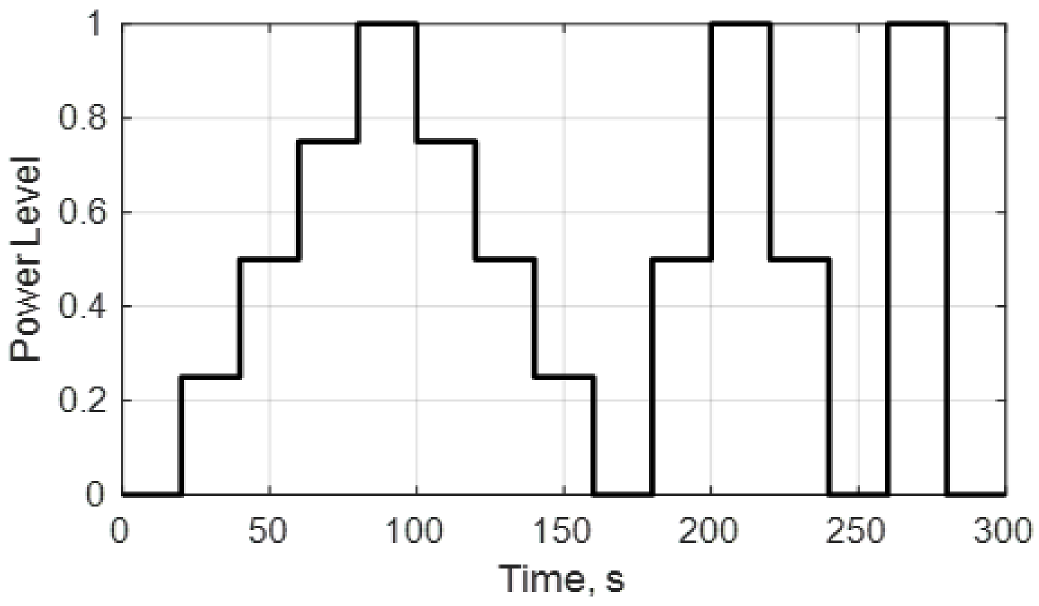


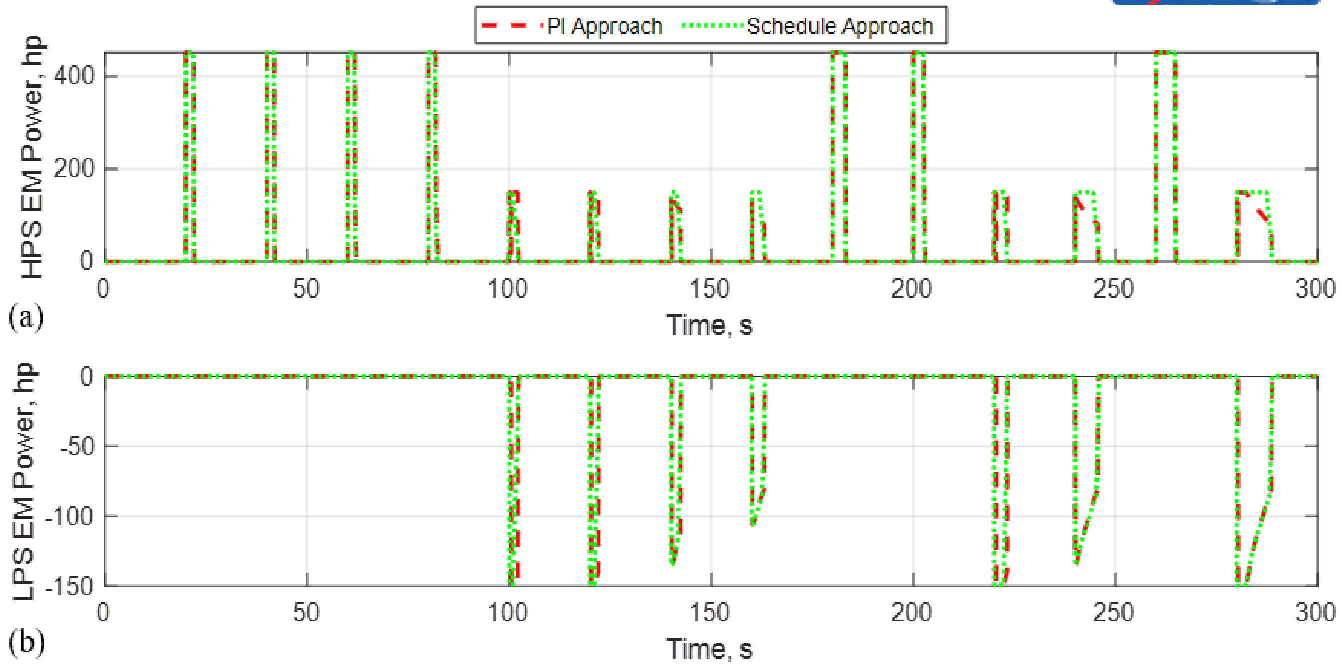




- Derived a power schedule for each EM using the optimization data
- Leveraged optimized fuel flow transient limit schedules designed a priori

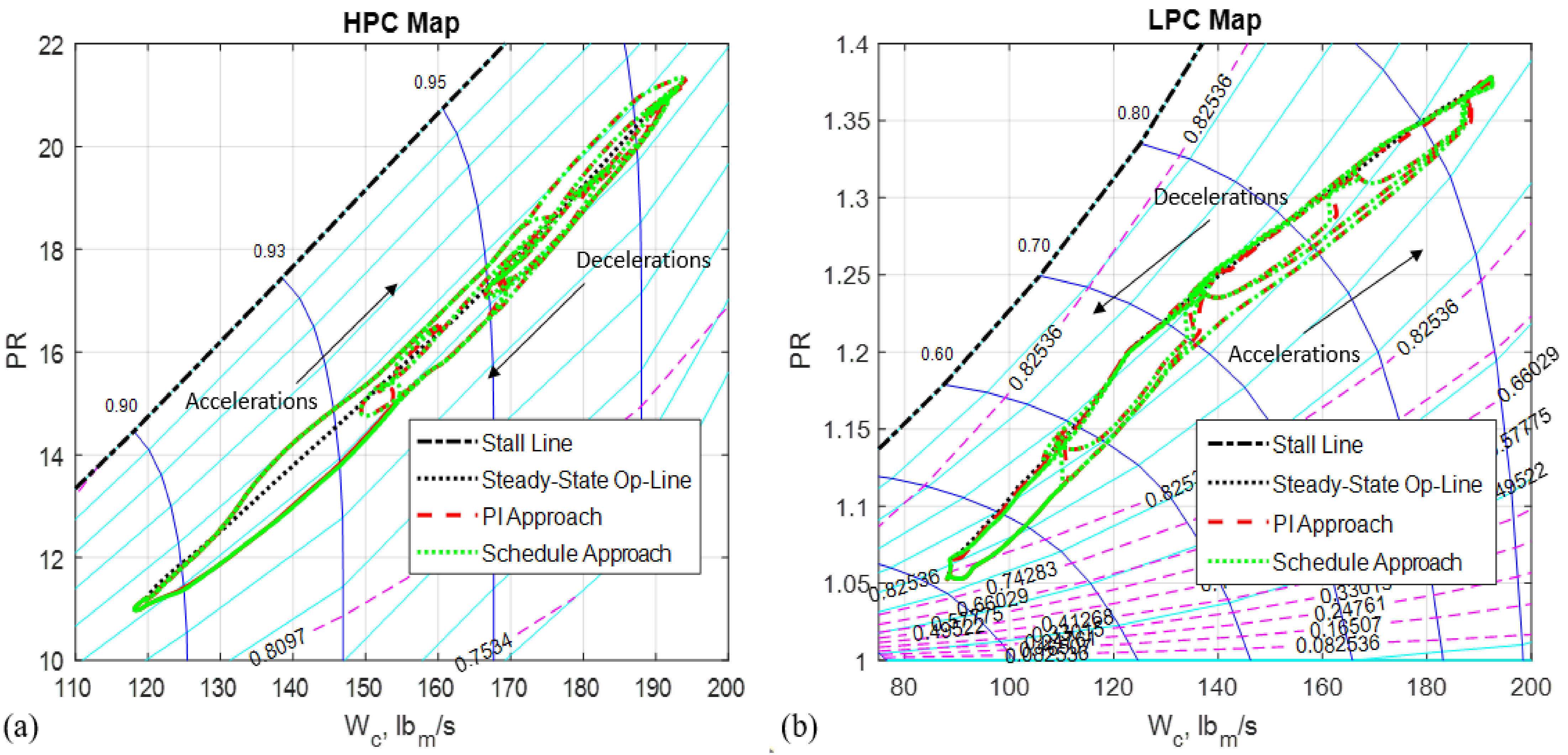
Schedule-Based Control Results





- Executed a series of burst and chop transients
- EOL engine assumed
- Optimized acceleration schedule utilized
- EM Limits: 150hp (LPS), 450hp (HPS)
- Power inputs are very similar

Schedule-Based Control Results



(a) (b)

Conclusions

- A genetic algorithm has been applied to optimize power system sizing and usage for implementing TEEM. Demonstrated:
  - EM power can be reduced by 200-400 hp with optimized w_f transient limit logic
  - TEEM enables significant benefits of ~3-4% TSU per 100 hp of injection during accelerations and up to 3.5% TSU per 100 hp of transfer during decelerations
  - Results from such an analysis could guide power system sizing decisions
- The schedule-based control approach appears to result in near optimal performance with simpler implementation
  - Demonstrated similar performance to a closed loop approach with less complexity
- Potential directions for future work
  - Further exploration of the scheduled-based control approach for implementing TEEM in other applications

Acknowledgments

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Questions/Discussion

Contact Information

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EXTRA CHARTS

Objectives

- Apply optimization techniques to optimize the use of an electrical power system for improving *transient operability of an electrified turbofan
- Evaluate the optimized solutions against a baseline
- Explore the response time, operability, and electrical system requirement trade space
- Derive a schedule-based approach implementing the operability control from optimized results
- Compare the schedule-based approach to a prior proposed approach

* Transient refers to and change in engine power/thrust demand associated with acceleration or deceleration of the engine shafts.

Contents and Organization

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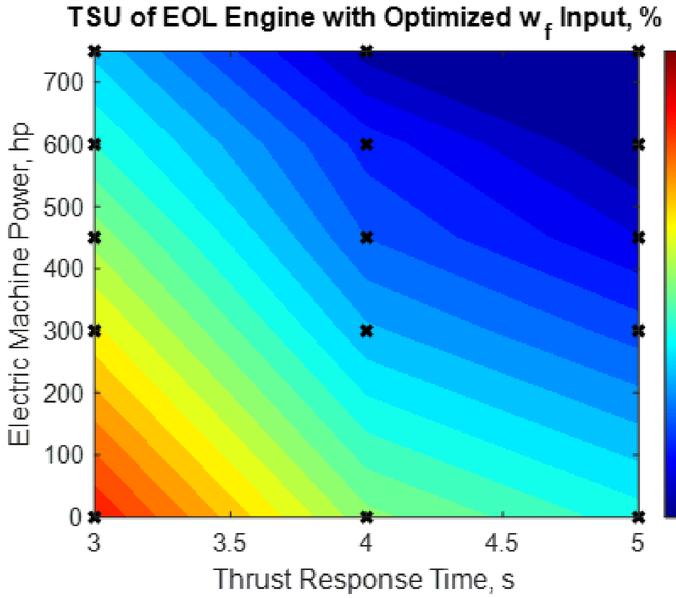
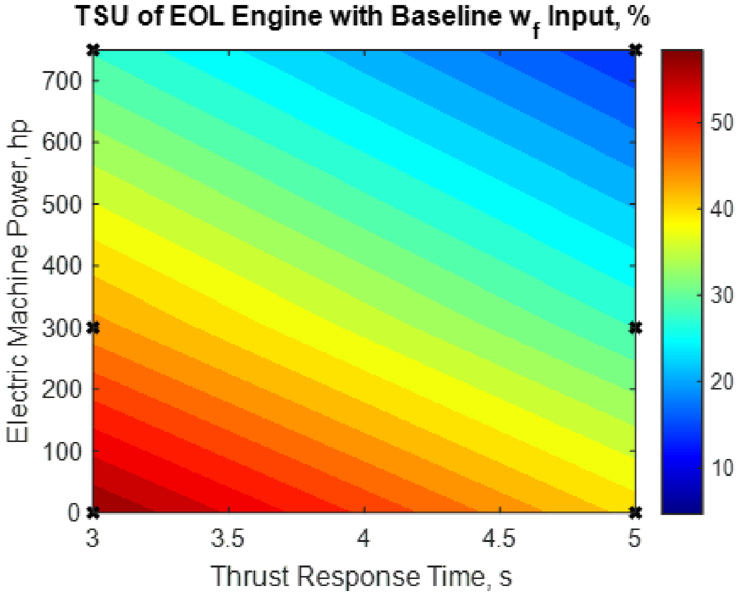
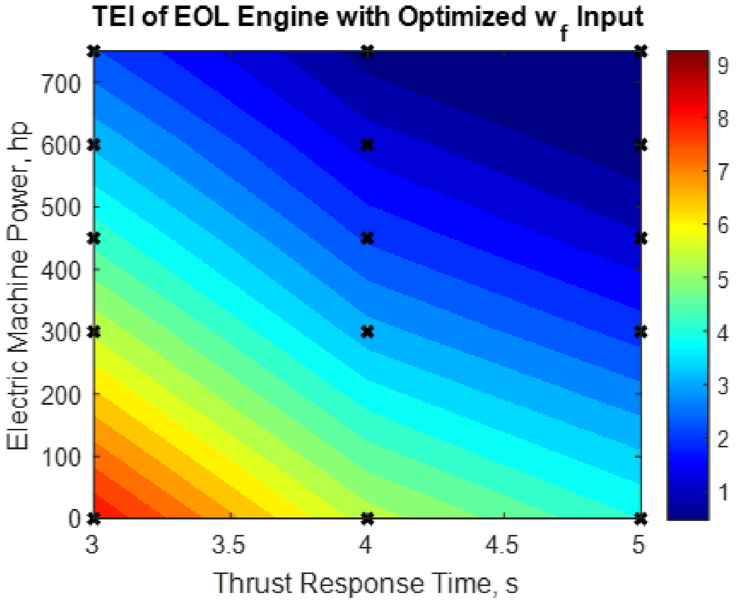
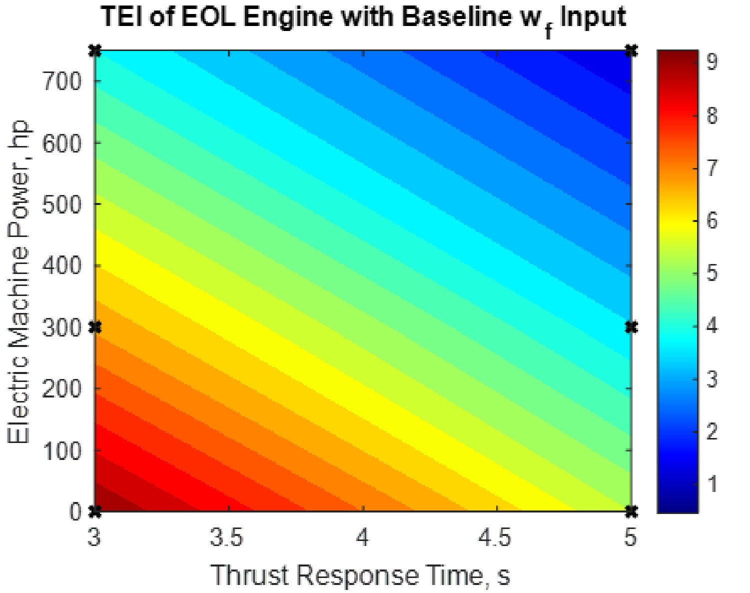
- Overview of the Optimization Approach
- Application for Illustrating the Approach
- Transient Optimization Results
- Schedule-Based Control Strategy Results
- Conclusions

Optimization Results – Trade Space Analysis - Acceleration

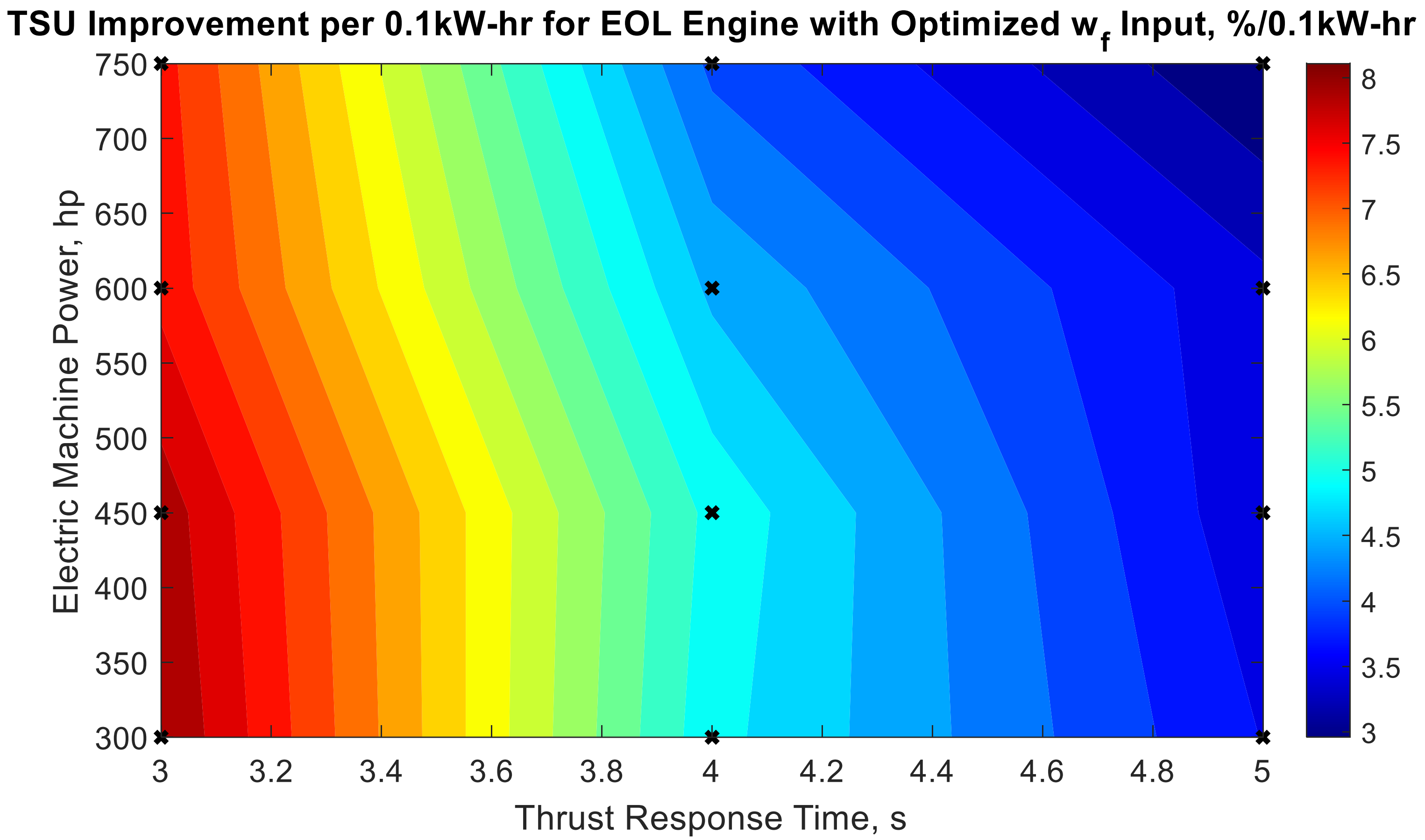




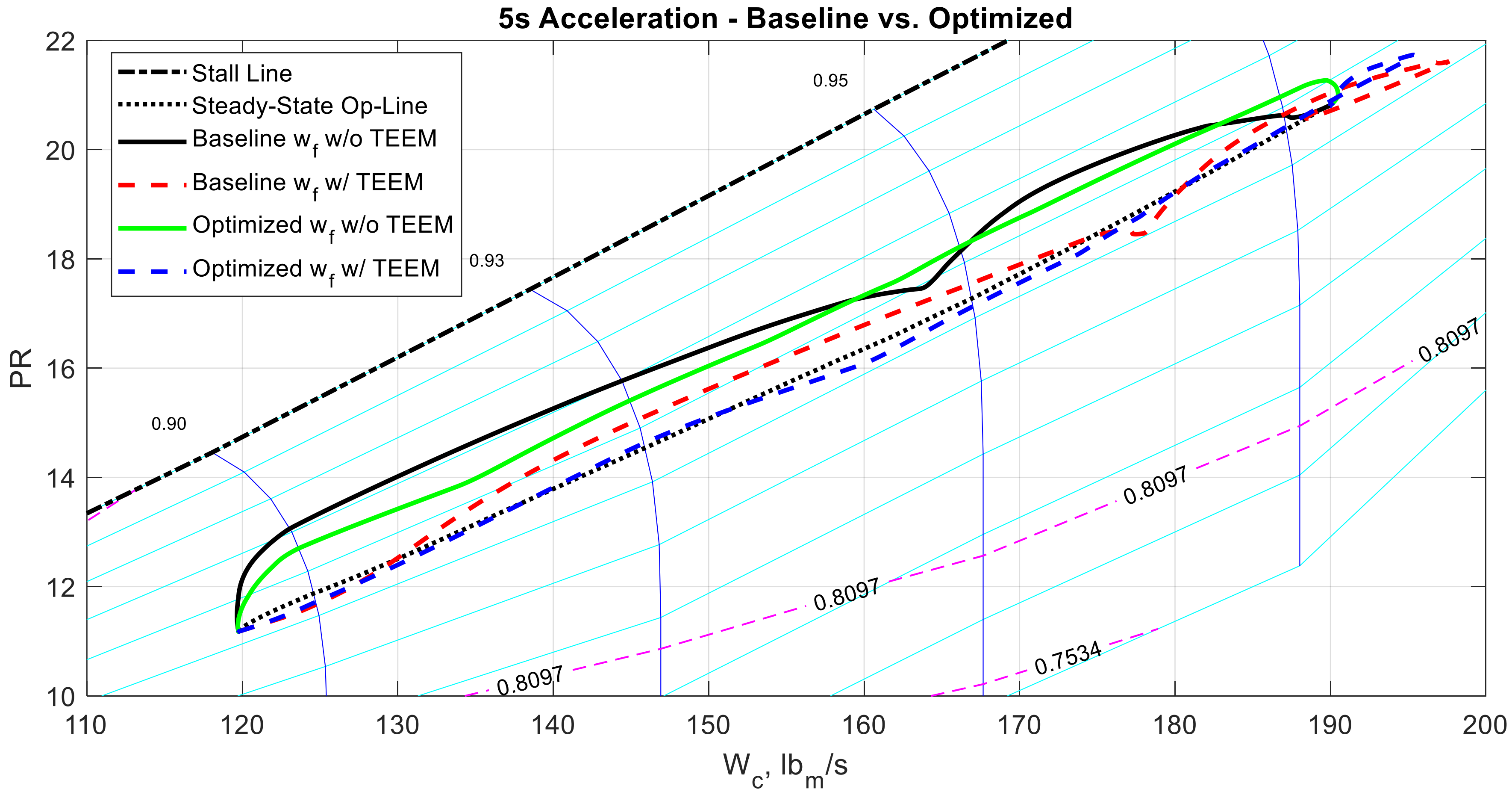




Optimization Results – Trade Space Analysis - Acceleration



Optimization Results – Trade Space Analysis - Acceleration



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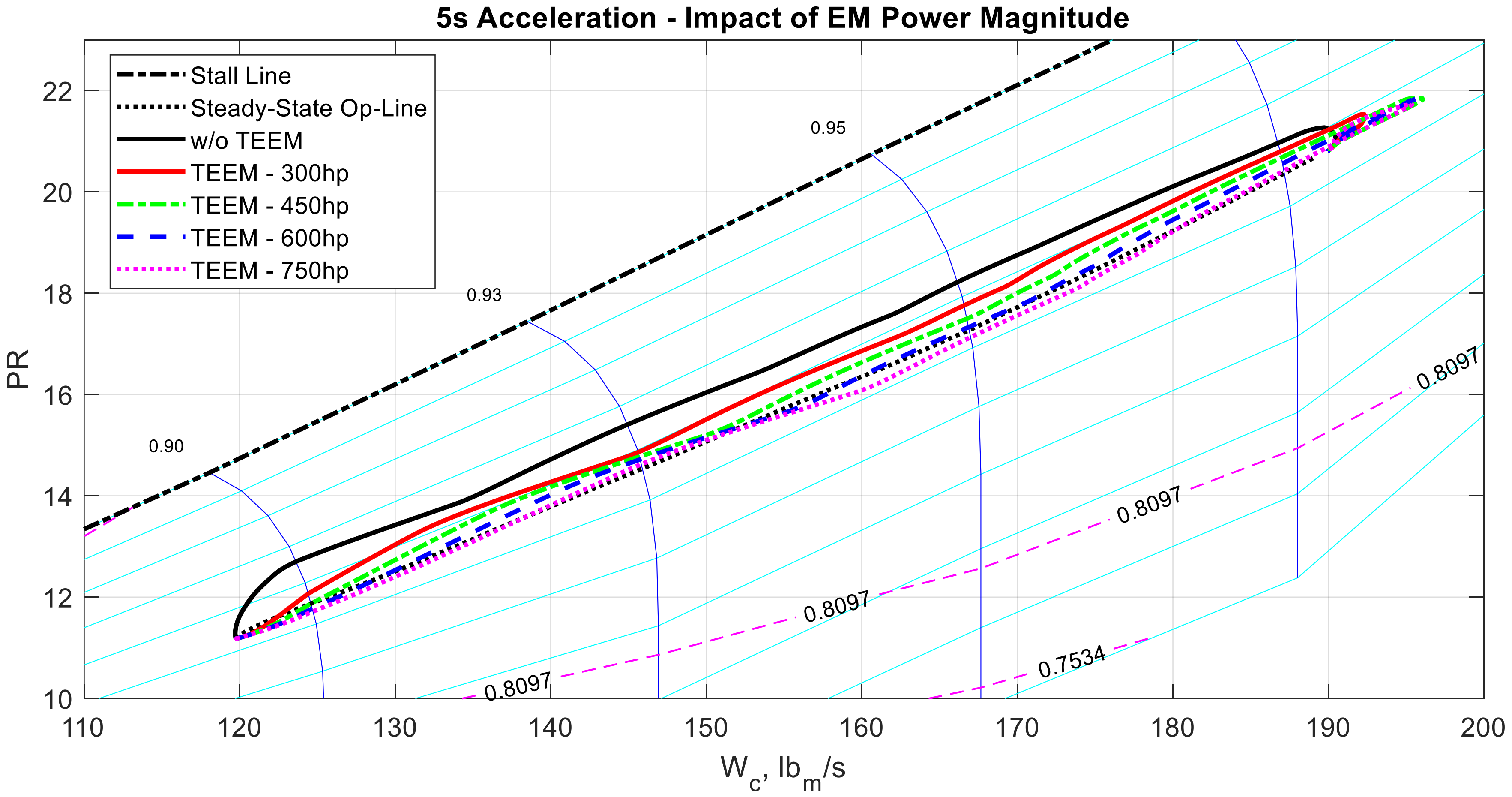
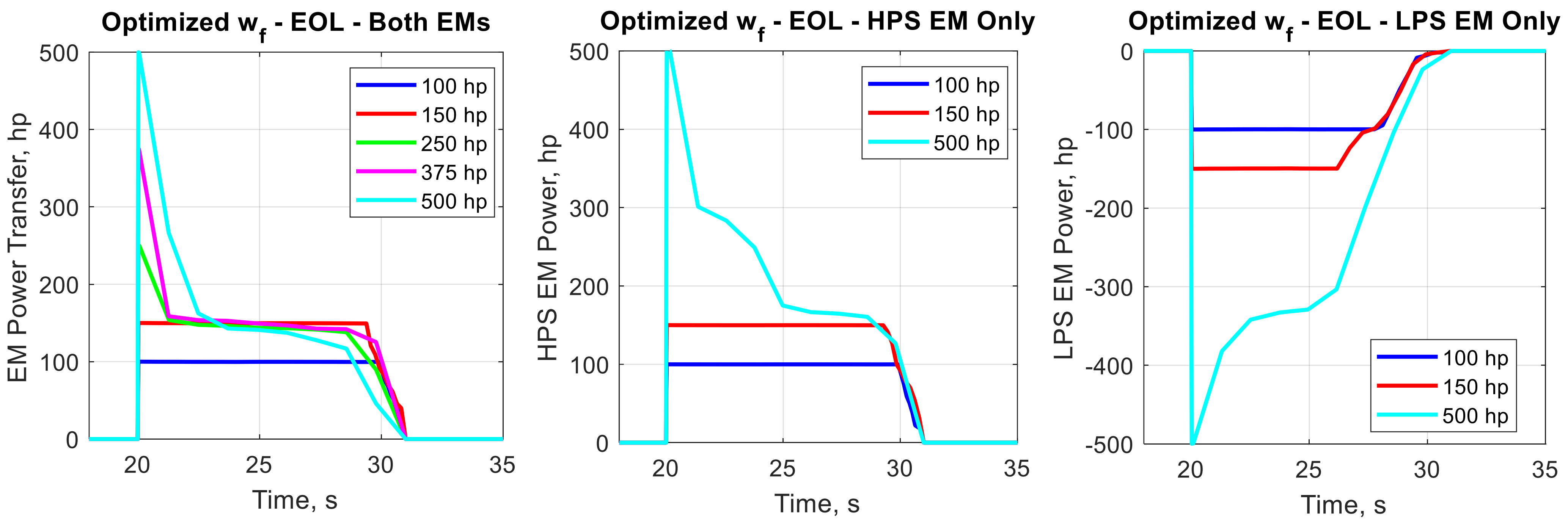


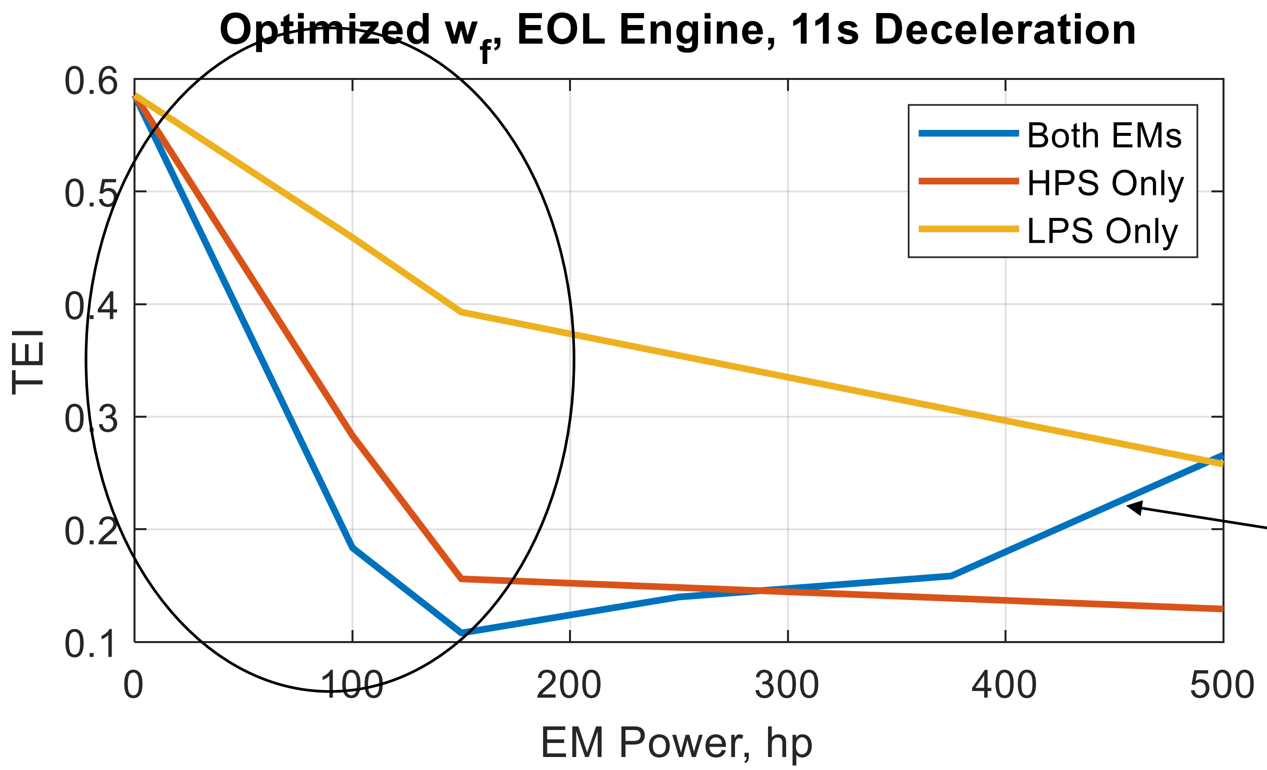
Optimization Results – Trade Space Analysis - Deceleration



- Based on power levels, order of effectiveness appears to be power transfer, power injection on the HPS, and power extraction on the LPS
- No reason to have an electric machine much larger than 150hp with power transfer

Optimization Results – Trade Space Analysis - Deceleration

Power transfer is able to achieve the same TEI as the HPS only and LPS only options with 75% and 33% of the power magnitude, respectively



Increase due to pushing of the running line below the steady-state operating line